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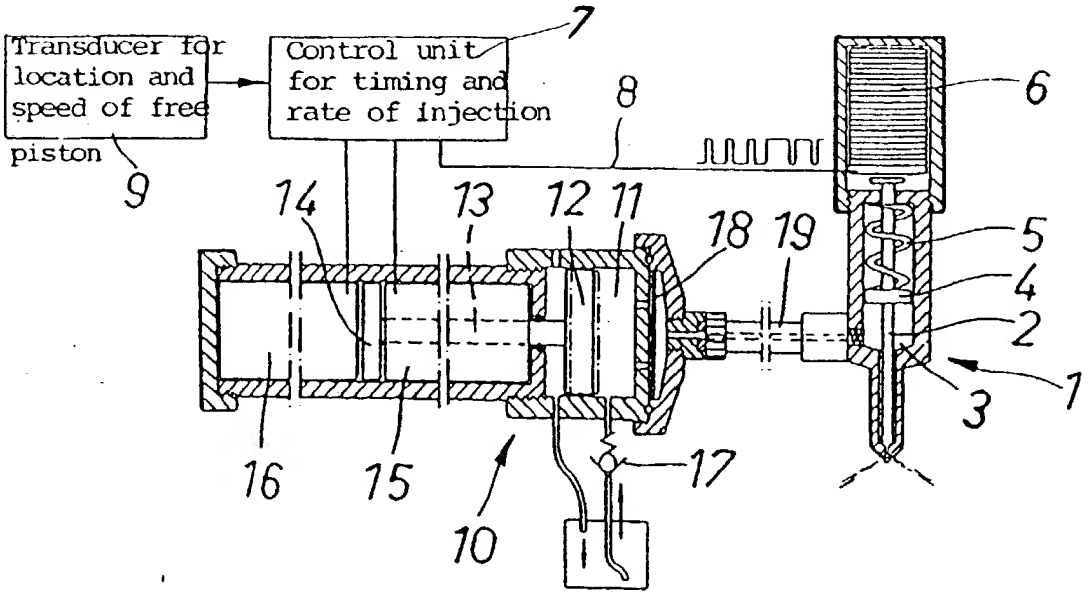
(54) Title: METHOD AND APPARATUS FOR CONTROLLING THE INJECTION OF FUEL




(57) Abstract

The invention relates to a method and apparatus for controlling the injection of diesel fuel. The opening of a needle (2) included in an injection nozzle (1) is subjected to a mechanical action by a piezoelectric actuator (6). Thus, the timing and rate adjustment of injection can be controlled by means of electronics (7), which delivers electrical control pulses to the actuator (6). The invention can be applied in a free-piston engine whose operation is controlled by adjusting the timing and rate of fuel injection.

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Method and apparatus for controlling the injection of fuel.

The present invention relates to a method for controlling the injection of fuel, in which method the fuel is delivered under pressure to an injection nozzle, the injection being effected therefrom by using the power of a piezoelectric actuator for operating a needle shutting off the nozzle.

The invention relates also to an apparatus for controlling the injection of fuel from an injection nozzle provided with a high-pressure fuel pump and an opening mechanism for a needle, including a piezoelectric actuator.

A particular application of the invention is a method for controlling the injection of fuel into the combustion chamber of a free-piston engine for gaining a complete control over the action of a free-piston engine by regulating the rate and/or timing of fuel injection.

US Patent publication 4,628,881 discloses several different solutions for an injection nozzle, wherein a solenoid valve controlled by an electric signal admits pressurized fuel into a hydraulic pressure booster or directly into a pressure accumulator. The amount of fuel is measured in the pressure booster or by the timing of a signal shutting off the solenoid valve.

Patent publications DE-1751543, EP-0218895 and EP-0219669 disclose the use of a piezoelectric actuator in a needle opening mechanism. These involve the use of piezolelectric tablets made of a hard, brittle ceramic material. The expansion of a single tablet is small and it is difficult to make a pile of tablets capable of withstanding the

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loads involved. The cited publications pay no particular attention as to how it is possible to synchronize the timing and rate control of fuel injection accurately to the actions of an engine piston and the requirements of a varying load.

An object of the invention is to develop an improved method and apparatus providing a simple and robust mechanism for achieving an all-round and accurate control over the injection of fuel. This object is achieved by means of the invention on the basis of the characterizing features set forth in the annexed claims.

The injection control process can be readily governed by means of electronics. The piezoelectric actuator provides a high operating speed and, if necessary, it is possible to produce pulse-width modulated opening cycles e.g. for a stratified feed or so-called pre-injection. The piezoelectric actuator can be built inside an injection nozzle as a compact unit, which is supplied with pressurized fuel and control pulses.

One of the major obstacles to the development of free-piston engines has been the control over the piston actions with a varying load and fuel feed. The invention offers an excellent solution to this problem in that the timing and/or rate of injection is controlled or regulated by the power of a piezoelectric actuator and the piezoelectric actuator is controlled by means of electric pulses, whose timing is determined by means of a signal delivered by a transducer sensing the position of the engine piston.

When the invention is applied to a free-piston engine, it is possible to achieve a virtually automatic regulation of

power such that, with a varying load, the output provided by an engine varies accordingly. The engine reacts quickly to load variations during the course of a single compression stroke and, thus, even a sudden drop of load does not result in a gable-hitting piston stroke. Neither does a sudden increase of load result in an engine shutdown. Thus, the operator is only required to take care of the operation of load-regulating hydraulic valves according to a desired or required load.

The invention will now be described in more detail by means of exemplary embodiments with reference made to the accompanying drawings, in which

fig. 1 shows a simplified basic view of of an apparatus of the invention for the injection of diesel fuel and for controlling the injection;

fig. 2 shows an example of how the fuel feeding rate may vary as a function of time, such that the actual injection (I) is preceded by a pre-injection (PI). The figure also shows injection control pulses, whose pulse width is modulated to match the injection rate;

fig. 3 shows various embodiments for fitting a piezoelectric actuator in relation to the needle of an injection nozzle; and

fig. 4 shows schematically a free-piston engine, wherein the injection of fuel is controlled with a method and apparatus of the invention.

An injection nozzle 1 shown in fig. 1 included a needle 2 provided with a plunger 4, having therebelow a pressurized

fuel chamber 3 and above a spring 5 for pressing the needle 2 to a shut-off position. When the pressure in chamber 3 increases sufficiently, the needle 2 rises against the force of spring 5 and the nozzle opens. In the present case, however, the rise of said needle 2 is partially or completely prevented by means of a piezoelectric actuator 6 until the opening rise of needle 2 is allowed by the control of actuator 6. The pulse-width modulation of control pulses being delivered to the piezoelectric film package 6 can be used for the accurate and high-speed control of the length of said film package 6, whereby the commencement, rising speed, and rising distance of the opening rise of needle 2 can be accurately and speedily adjusted. For example, the arrangement may be such that the film package 6 extended by a large pulse width prevents the rise of needle 2 partially or completely and reducing the pulse width serves to control the shortening of film package 6 and the rise of needle 2. The control pulses are delivered from an electronic unit 7 via a control line 8. The electronic unit 7 includes a necessary control logic for the timing and rate regulation of injection. If the question is about the injection of diesel fuel into a free-piston engine, the electronic unit 7 receives the information (in addition to the preset parameters) required for timing from a transducer 9 sensing the location and operating speed of the free piston.

Although the fuel pump can be of any known type, fig. 1 discloses an embodiment of the invention in which an injection pump 10 is also operated by the power of a piezoelectric actuator. A cylinder space 11 contains a piston 12 carrying a flange 14 at the end of its piston rod 13. On either side of the flange 14 there are piezoelectrically extensible and reducible elements 15, 16

(either one of which can also be replaced by a spring). Since piezoelectric elements are capable of producing very significant forces, the length of stroke can be increased by means of a lever mechanism, if necessary. The injection of fuel is initiated by a pumping stroke performed by the piston 12 and produced by the electric control pulses of the piezoelectric elements 15, 16 received from the electronic unit 7. During the return stroke of piston 12 a one-way valve 18 prevents the discharge of pressure through a fuel feeding pipe 19 and the cylinder space 11 receives more fuel through a one-way valve 17.

If the piezoelectric actuator 6 is not supplied with any control pulses at all or the width of control pulses is very narrow, the needle 2 will be able to open partially or completely as a result of a pressure stroke received from the pump 10. Thus, as a matter of fact, the pump 10 serves as a piezoelectric actuator, which determines the opening moment and speed of needle 2. However, as the question is about very short operating distances and small amounts of fuel, the accurate control over injection can be best achieved by means of the piezoelectric actuator 6 having a direct effect on the control of needle 2.

Fig. 3 illustrates an alternative arrangement, wherein a piezoelectric actuator 6a, upon extending, carries a needle 2 in the opening direction against the force of a spring 5'. Thus, the spring will be able to operate as a sort of relief valve at the malfunction of the piezo-system and, in that case, the injection nozzle only operates at an opening pressure higher than normal. The top end of needle 2 is provided with a flange 2a between piezoelectric actuator 6a and spring 5'. Fig. 3b illustrates the preparation of the piezoelectric element 6a by winding a piezoelectric film material in a spiral

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fashion around the needle 2. In fig. 3c, the piezoelectric element 6a is prepared from a film tape by pleating and the needle 2 extends through a hole in the middle. Such piezoelectric film materials are commercially available products. One example is the KYNAR piezo film which is available in varying thicknesses, the final element consisting of several laminated film layers. Between two electrically conducting films there is a piezoelectric material, e.g. PVDF, whose dimension changes slightly in one or more predetermined directions as a voltage is switched on between the electrically conducting film sheets. The change of dimension is directly proportional to the strength of voltage and inversely proportional to the thickness of a film sheet. If the question is about a pulse-shaped voltage with a sufficiently high pulse frequency, the change of dimension corresponds to the effective value of the voltage instead of the peak value of an individual pulse. Thus, the change of dimension of a piezoelectric element 6, 6a can be regulated by modulating the width of the control pulses.

Fig. 2 illustrates a basic example, wherein the narrow pulses delivered to a piezoelectric actuator 6a are used for achieving the pre-injection "PI" of fuel and the wide pulses are used for achieving the actual injection "I". It is prior known that the use of pre-injection results in a cleaner and more complete combustion. By means of the invention it is easy to adjust the injection rate in relation to the duration of an injection cycle in any desirable way. It is experimentally possible to find an injection pattern and an individually injectable fuel dose to achieve a preferred efficiency and lower emissions as a result of a more complete combustion.

Fig. 4 illustrates an application of the invention

relating to a free-piston engine. In the engine, the opposite ends of a piston rod 22 are fitted with engine pistons 23 and 24. The piston assembly 22, 23, 24 operates in a reciprocating fashion and produces power directly in a hydraulic form by means of a hydraulic cylinder 25 mounted on the piston rod 22.

The actions of said piston assembly 22, 23, 24 is monitored e.g. by means of an incremental transducer 9a, 9b, which delivers a number of pulses proportional to the operating distance of the piston assembly. The pulse transducer includes a screw-threaded axle 9a, which is carried along with the piston assembly and has the passes of the ridges of its threading identified by means of a magnetoresistive identification transducer 9b. By disposing a number of transducers 9b around the threaded axle 9a, e.g. at a 90° angular distance from each other, it is possible to achieve an increase of resolution and at the same time a possibility of determining the traveling direction, since the order or sequence of pulses delivered by the threads is reversed on transducers 9b as the operating or traveling direction reverses. The number of pulses received from the transducers 9b can be used as a basis for accurately determining the location of the piston assembly. The speed determination for the piston assembly can be effected by calculating the number of pulses received from transducer 9b per unit time. A change in the speed of the piston assembly can be determined by monitoring the changes of pulse rate. An electronic unit 7 is used for carrying out an analysis on the operating status of the piston assembly and, on the basis of this analysis, the piezoelectric actuator 6 is controlled in such a manner that the timing and rate of fuel feeding are related to the operating status of the piston. For example, if the piston 23 approaches the cylinder gable at

a faster-than-normal speed, the pre-injection of fuel is initiated with plenty of time left and at a sufficient rate so that the piston can be stopped in order to avoid a gable-hitting stroke. The actual injection for a working stroke is not initiated until after the combustion of pre-injected fuel has sufficiently decelerated the action of the piston. When the rate and commencing moment of fuel injection are adjusted by means of a signal received from a transducer 9a, 9b sensing the operating speed and a change in the operating speed of an engine piston, it is possible to carry out an automatic control over the output of an engine in such a manner that, as the load varies, the output provided by an engine varies accordingly. In order to conclude that the question is about changes in the operating status of a piston definitely caused by load fluctuations, the speeds of a piston assembly within the its mid-section and when approaching the gable are compared with each other. Naturally, the comparison of speeds can be done in any of the various stages of a compression stroke, i.e. at points separated from each other by the length of a piston assembly in the operating direction thereof.

The greater the deceleration of action, the greater is the load and, accordingly, the injection nozzle 1 must be controlled for delivering a larger dose of fuel. The control of fuel injection of the invention responses quickly and over its entire control range during the course of a single compression stroke and, thus, the actions of a piston assembly are always controlled despite quick and major fluctuations in the load.

The case shown in fig. 4 involves the use of mechanical injection pumps 20, which are disposed in a manner such that the axially operating pumping elements thereof

receive their driving force from the collision of the skirts of pistons 23 and 24. Thus, the fuel to be injected can be provided with a correctly timed pressure pulse and the actual fine tuning of the injection is effected according to the invention by means of a piezoelectric actuator 6 or 6a. If the axial extension of the illustrated engine unit is fitted with another engine unit (the end of which is shown by dash-and-dot lines), the fuel injection pumps 21 of this other engine unit are controlled on the basis of the actions of the same piston assembly 22, 23, 24, whereby the piston assemblies of different engine units can be operated simultaneously in the opposite directions. Hence, this achieves the vibration absorption for an engine merely by adjusting the timing of injection in different engine units. Instead of mechanical injection pumps 20 and 21 it is naturally possible to employ in fig. 4 a piezoelectric pump 10 as shown in fig. 1. This requires a data transmission link 26 between the electronic units 7 controlling the injection of different engine units, so that the basic control over the injection of both engine units is received from the actions of one and the same piston assembly. The timing and rate control of the injection of different engine units in accordance with the invention can be effected either independently of each other on the basis of a control received from the operation transducers of the corresponding piston assemblies or also under the control of the operation transducer of one and the same piston assembly. The latter requires a symmetrical loading for both engine units.

The above exemplary embodiments are intended for illustrating principles of the invention and are not described in the sense of limiting the invention. It is obvious that a skilled person can exploit the invention by

modifying and combining it with various structural designs. For example, the piezoelectric pump 10 and the injection nozzle 1 can be designed as a single compact unit.

Claims

1. A method for controlling the injection of fuel, in which method the fuel is delivered under pressure to an injection nozzle (1), the injection being effected therefrom by using the power of a piezoelectric actuator (6, 6a) for operating a needle (2) shutting off the nozzle, c h a r a c t e r i z e d in that the actuator (6, 6a) comprises a film layer package prepared from a piezo film by winding or pleating, that during each individual injection the actuator is supplied with several electrical control pulses, whose pulse width and/or rate has an effect on the operating distance of the needle (2), and that the timing of said control pulses is determined depending on the location and/or speed of the piston of an engine for adjusting the timing and injection rate of each individual injection.

2. A method as set forth in claim 1, c h a r a c t e r - i z e d in that the needle (2) is shifted to an opening position by means of a piezo film package (6a), the needle (2) extending therethrough and the opening of said needle (2) being also timed by means of said control pulses.

3. A method as set forth in claim 1, c h a r a c t e r - i z e d in that a first stage in the opening process of the needle (2) is produced by the pressure of fuel and further opening of the needle (2) is resisted at least over some of its maximum opening distance by the power of said piezoelectric actuator (6), whereby a second stage in the opening process of the needle is timed by means of said electrical control pulses.

4. A method as set forth in any of claims 1-3, c h a r - a c t e r i z e d in that the fuel is pressurized by the

power of a second piezoelectric actuator (15, 16).

5. A method as set forth in claim 4, c h a r a c t e r - i z e d in that the pressure periods of fuel feeding are timed by delivering electrical control pulses to said second piezoelectric actuator (15, 16).

6. A method as set forth in any of claims 1-3, c h a r - a c t e r i z e d in that the electrical control pulses of said piezoelectric actuator (6, 6a) are timed on the basis of a signal delivered by a transducer (9a, 9b) sensing the location of an engine piston (23, 24).

7. A method as set forth in claim 6, c h a r a c t e r - i z e d in that said control pulses are timed on the basis of a signal delivered by the transducer (9a, 9b) sensing the location and operating speed of the piston (23, 24).

8. A method as set forth in claim 6 or 7, c h a r a c - t e r i z e d in that the actual injection of fuel is preceded by a quantitatively minor pre-injection, whose rate and commencing moment are adjusted by means of a signal received from said transducer (9a, 9b).

9. A method as set forth in claim 7, c h a r a c t e r - i z e d in that the speeds of the engine piston assembly are compared at points separated from each by a distance in the operating direction and the result of such comparison is the basis for adjusting the fuel injection rate.

10. The application of a method as set forth in claim 6, 7, 8 or 9 for controlling the injection of fuel into the combustion chamber of a free-piston engine.

11. An apparatus for controlling the injection of fuel from an injection nozzle (1) which is provided with a high-pressure fuel pump (10; 20) and includes an opening mechanism for a needle (2) provided with a piezoelectric actuator (6, 6a), controlled by electrical pulses which determine the adjustment of the timing and rate of injection, c h a r a c t e r i z e d in that the actuator comprises a film layer package (6, 6a) prepared from a piezo film by winding or pleating and that said electrical control pulses are produced in an electronic unit (7), which is provided with a transducer (9a, 9b) sensing the location of a piston (23) and which delivers several control pulses during each individual injection.

12. An apparatus as set forth in claim 11, c h a r a c - t e r i z e d in that the needle (2) extends through said film layer package (6a).

13. An apparatus as set forth in claim 11, c h a r a c - t e r i z e d in that said fuel pump (10) includes a second piezoelectric actuator (15, 16) for producing the mechanical pumping actions of the pump (10).

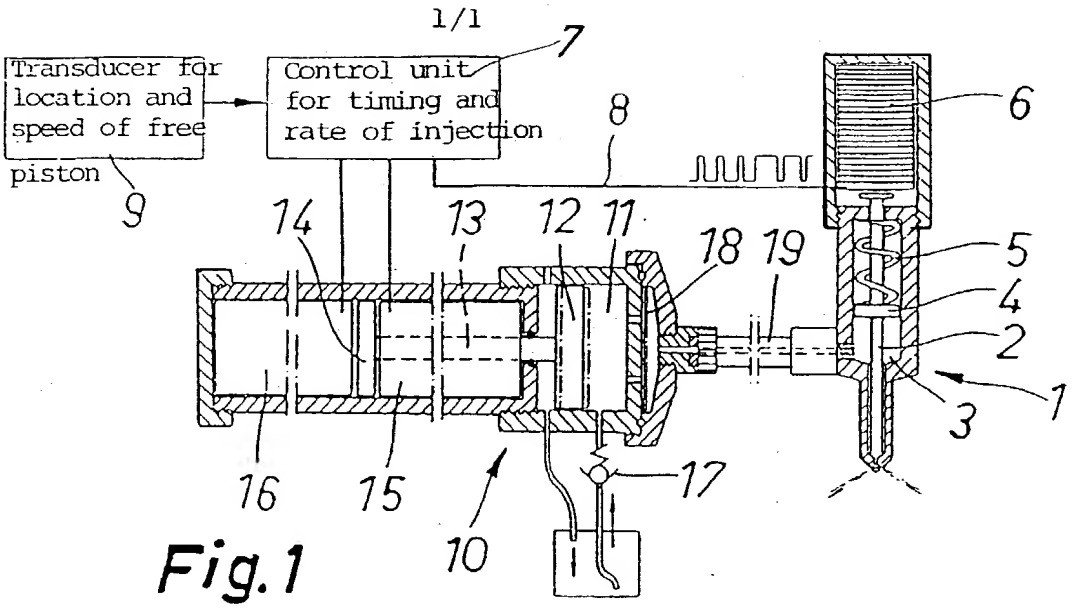


Fig. 1

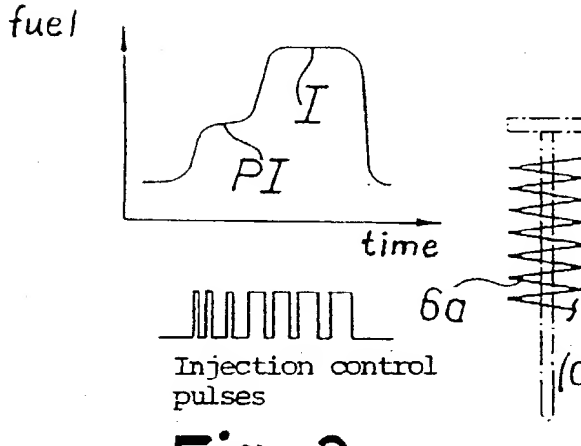


Fig. 2

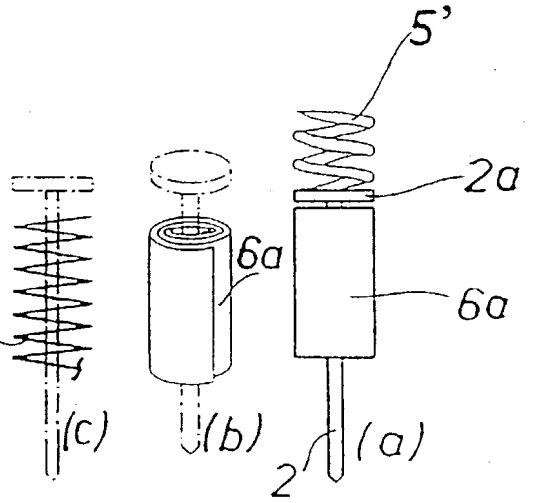


Fig. 3C Fig. 3B Fig. 3A

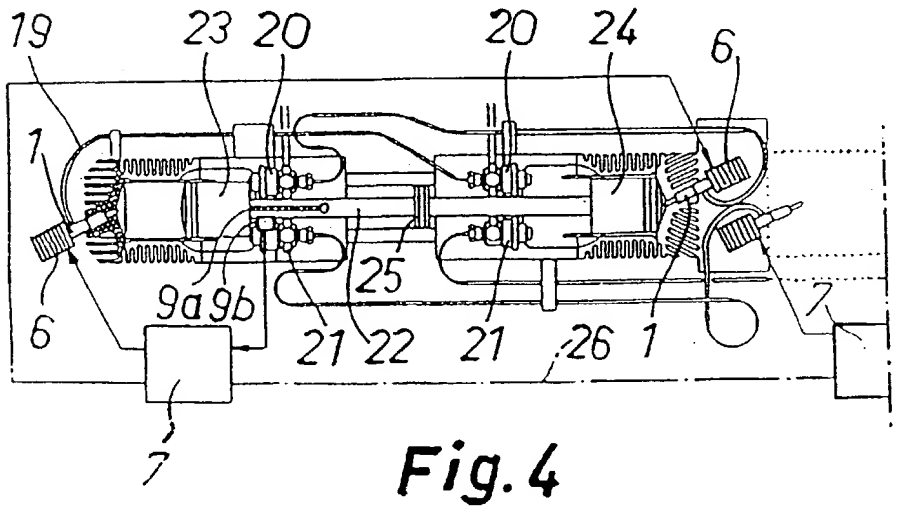


Fig. 4

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International application No.
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## A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)

IPC 5 : F02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CLAIMS, WPI

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US, A, 4649886 (IGASHIRA ET AL), 17 March 1987 (17.03.87), column 3, line 24 - column 4, line 30, figures 1,2 | 1-13 |
| Y | Patent Abstracts of Japan, Vol 11,No 175, M-596, abstract of JP, A, 62-7967 (TOYOTA MOTOR CORP), 14 January 1987 (14.01.87), details 26-28,40 | 1,3-11,13 |
| Y | DE, A, 1809465 (KLÖCKNER-HUMBOLDT-DEUTZ AG), 24 Sept 1970 (24.09.70), figure 1, page 4, last part - page 6 | 2,12 |

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | US, A, 3391680 (G.M. BENSON), 9 July 1968 (09.07.68) -- -------- | 1-13 |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

26/02/94

International application No.
PCT/FI 94/00041

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| US-A- 4649886 | 17/03/87 | DE-A,C- 3338741 | 26/04/84 |
| | | JP-C- 1699357 | 28/09/92 |
| | | JP-B- 3063664 | 02/10/91 |
| | | JP-A- 60017250 | 29/01/85 |
| | | US-A- 4499878 | 19/02/85 |
| | | JP-A- 60043146 | 07/03/85 |
| | | JP-C- 1765406 | 11/06/93 |
| | | JP-B- 4057857 | 14/09/92 |
| | | JP-A- 59087238 | 19/05/84 |
| DE-A- 1809465 | 24/09/70 | NONE | |
| US-A- 3391680 | 09/07/68 | NONE | |